Elevation information in tail (EIT) technique for lidar altimetry

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Abstract: A technique we refer to as Elevation Information in Tail (EIT) has been developed to provide improved lidar altimetry from CALIPSO lidar data. The EIT technique is demonstrated using CALIPSO data and is applicable to other similar lidar systems with low-pass filters. The technique relies on an observed relation between the shape of the surface return signals (peak shape) and the detector photo-multiplier tube transient response (transient response tail). Application of the EIT to CALIPSO data resulted in an order of magnitude or better improvement in the CALIPSO land surface 30-meter elevation measurements. The results of EIT compared very well with the National Elevation Database (NED) high resolution elevation maps, and with the elevation measurements from the Shuttle Radar Topography Mission (SRTM).

OCIS codes: (010.3640) lidar.

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1. Introduction of CALIPSO vertical profiling lidar and surface signal

The question we address in this paper is whether Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) can determine surface elevation to better than its nominal 30 meter sampling resolution. The CALIPSO space-craft carries a dual wavelength (532nm/1064nm), polarization sensitive lidar for profiling the aerosols and clouds in the atmosphere. Components of the backscattered signal both parallel and perpendicular to the

#85436 - $15.00 USD Received 19 Jul 2007; revised 25 Sep 2007; accepted 3 Oct 2007; published 19 Oct 2007

linearly polarized output beam are separated in the receiver optics and measured separately. The Nd:YAG laser transmitter, with a 20 Hz repetition rate, has a pulse width of about 20 ns, equivalent to a length of ~6 meters. The backscattered signal is digitally sampled at an initial resolution 15 meters range resolution at both 532 nm and 1064 nm. To conserve bandwidth, the data acquired between -0.5-km below and 8.3-km above mean sea-level are subsequently averaged on board the satellite to vertical resolutions of 30 meters (532 nm) and 60 meters (1064 nm). The lidar utilizes a 40 MHz master clock from which all the system timing for both the laser and receiver electronics is synchronized. The receiver utilizes fourteen bit, 10 MHz analog-to-digital convertors (ADCs). These units were the fastest radiation hardened ADCs available at the time, and are adequate to meet the requirement for characterizing the atmosphere. Each receiver channel uses two ADCs that have their dynamic ranges autonomously adjusted so that the combined merged and scaled output achieves a nominal 23 bit signal resolution. On-board algorithms utilize the satellite's global positioning system (GPS) data, attitude data (from star-trackers), and a geoid model of the Earth to accurately reference the timing of each individual laser pulse to mean sea level (MSL). This procedure allows additional onboard averaging to be carried out in the horizontal (along-track) dimension, thus further reducing downlink bandwidth requirements. This additional averaging is confined to the upper troposphere and stratosphere; in the lower troposphere (-0.5-km to 8.3-km), backscatter data are delivered at single shot resolution.

The strongest of the CALIPSO backscatter signals are generated by ocean and land surfaces that are covered by snow and/or ice. In the 532nm parallel channel, the peak signals for snow and ice surfaces under clear skies are so strong that they usually saturate the digitizers. Unlike the parallel component, the cross-polarized (i.e., perpendicular) component of the ground returns for most land and ocean surfaces are generally not saturated.

For low resolution surface detection, the maximum backscatter value at the surface altitude indicates which 30-meter range-bin contains the land surface return. This is the current CALIPSO surface detection method. Due to the bandwidth of the electronics downstream of the detectors, the surface signal is spread by the instrument response function over several adjacent range bins. A low-pass Bessel filter implemented in the detector analog electronics distributes more than 90% the surface return energy over the three 30-meter vertical range bins starting from the bin that contains the surface echo. Additionally, the PMT detectors used for the 532 channels exhibit a very small but more slowly decaying transient signal in response to the strong surface return [1]. The 1064nm channel utilizes an avalanche photodiode detector for which the transient response is much faster.

Because the CALIPSO lidar system was optimized for measuring backscatter from clouds and aerosols, highly accurate ranging of the Earth's surface was not a mission objective. However, in this paper we show that even with CALIPSO's 20ns laser pulse and 30-meter vertical sampling, it is still possible to obtain surface elevation information that is accurate to within 2 meters or better.

2. The Elevation Information in Tail (EIT) technique

In this section we introduce the *elevation information in Tail* (EIT) concept, which is significantly different from conventional approaches to laser altimetry [2-5]. In the conventional laser altimetry, such as the Geoscience Laser Altimetry System (GLAS) aboard the Ice, Cloud and land Elevation Satellite (ICESat), laser backscatter energy as a function of time is recorded at a very high vertical sampling resolution (15 cm for GLAS). The recorded distribution of the backscattered energy (so called "waveform") is considered by the GLAS community as the height distribution of laser-illuminated surfaces and the location of the peak backscattered energy is the indication of the surface. The precision of this "waveform" technique is thus limited to the vertical sampling resolution. Apply this conventional altimetry concept to CALIPSO's profiling lidar, the best surface elevation resolution can be achieve is CALIPSO's vertical sampling resolution (30 meter). Instead of consider the backscattered energy before and after the peak surface backscatter as the surface returns, as what the conventional "waveform" technique implies, the Elevation in Tail (EIT) technique of this

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study consider the shape of the backscattered energy intensity distribution a result of instrument low-pass filter of a quasi-uniform surface and contains super-resolution vertical information. This paper introduces how the EIT technique reveals such a super-resolution.

Instead of deriving the surface elevation directly from the location of the surface peak return alone, the EIT method uses both the shape of the three peak surface backscatter range bins and characteristics of the PMT transient response immediately after the peak signal. The peak signal provides a coarse resolution indication of the surface altitude. Disentangling the relationship between the peak signal and the subsequent transient response reveals more accurate surface elevation.

For very short pulses and very fast vertical sampling, the shapes of the surface return and its sub-surface tail should remain stable, while the magnitudes of the peaks will vary with surface reflectance. Due to the relatively coarse 30-meter vertical resolution of the CALIPSO detection system, the surface backscatter energy can be partitioned unevenly across the three range bin spread of the low-pass Bessel filter, and thus the measurements of the transient response and its relation with the three surface backscatter range bins can vary, depending on the exact location of the surface within the 30-meter surface range bin. The overall shape of the surface signal and the after-pulse transient response is sensitive to the exact location of the surface within the 30-meter CALIPSO maximum backscatter surface range bin. The EIT technique derives surface elevation by taking advantage of this sensitivity.

Prior to launch, extensive laboratory characterization of the flight detectors and their associated electronics demonstrated that the CALIPSO PMT transient response remains the same for lidar surface returns with varying surface reflectance (signal strength), and that the transient response can be accurately estimated for a given input signal level. This can be independently verified using on-orbit data by studying CALIPSO's lidar signal from land surfaces, and comparing peak signals (peak) with after pulse transient response (tail). Land surface backscatter data indicate that the tail-to-peak signal ratios are independent of the surface reflectance. The ratios vary with the distance between the surface elevation and the center of surface bin.

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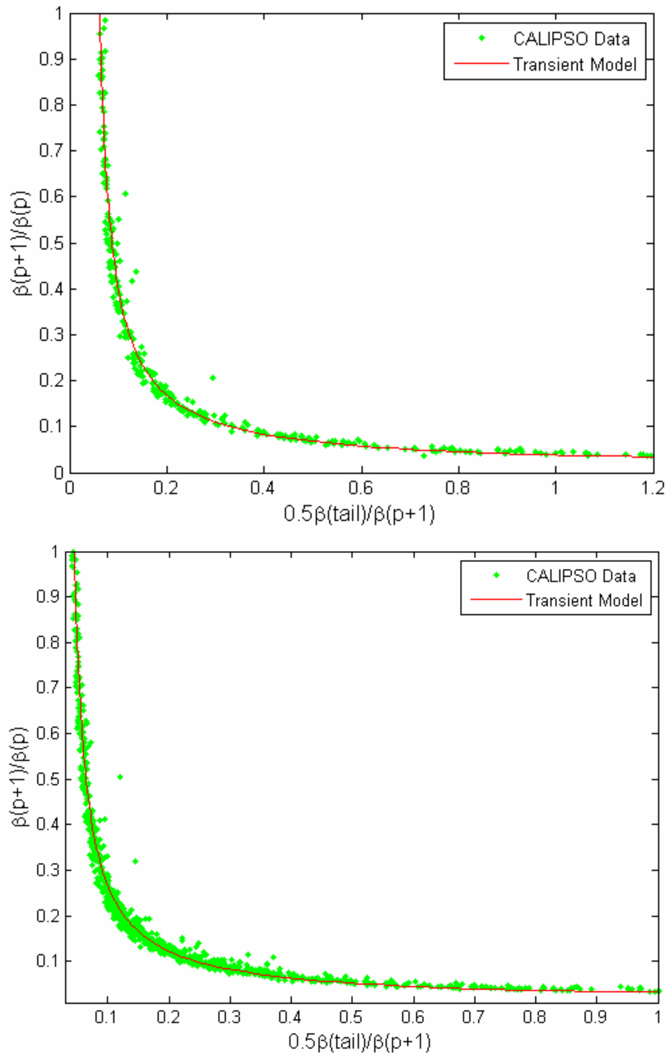

Fig. 1. Surface peak signal and detector transient response relation for CALIPSO single lidar shots. The y-axis is the range bin immediately after the peak, β(p+1), divided by the peak signal, β(p). The x-axis is the integrated return of ten range bins starting from the second range bin after the peak, 0.5β(tail)/β(p+1). The left and right panels are for two geographic locations of different orbits, with very different land surfaces.

Figure 1 shows examples of tail-to-peak ratios for CALIPSO land surface signals, with very different surface types and about an order of magnitude change in surface reflectance. Two different tail-to-peak ratios are considered in this figure. The Y-axis is the ratio of the first range-bin after the peak surface signal divided by the peak signal. The X-axis tail-to-peak ratio is the mean transient response tail (starting from the second range after the peak surface signal, and extending for 10 consecutive bins) divided by the signal value in the range bin immediately after the peak signal. Both the X and Y values are functions of the distance between the center of the peak 30-meter range bin and the surface elevation. If CALIPSO had a much shorter pulse and a much faster sampling rate, all the data in Fig. 1 would have collapsed to one single point, since the transient response is insensitive to surface types and

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reflectance. This would also be the case if the land surface were always located at the center of the CALIPSO's 30-meter surface range bin (i.e., the surface return was exactly coincident with the sample timing) and CALIPSO had a vertical sampling rate faster than 10 MHz. If, instead of being centered in a 30-meter bin, the actual surface location is moved upwards by several meters, the magnitude of the signal in the peak range will be reduced, as will the magnitude of the signal from the range bin immediately after the peak. Conversely, the signal magnitude in the range bin immediately after the peak will increase. In this case, the signal levels in the transient response tail will increase only slightly, and this concomitant increase is much less than the signal increases in the range bin immediately after the peak. When the center of the 30-meter range bin is approximately 15 meters below the land surface (i.e., when the surface lies at the top of the bin), the signals immediately before the surface and after the surface become almost identical. We have looked at hundreds of orbits with different surface reflectance and surface types and the tail-to-peak relation in Fig. 1 is always the same. Since all of the CALIPSO land surface measurements follow the same relationship, as shown in Fig. 1, we can conclude that the distance between the exact location of the land surface and the center of the 30 meter CALIPSO range bin is a function of the shape of the three peak range bins and the tail-to-peak signal ratio, and the shape of the surface and transient response relation is insensitive to surface reflectance and hence the curves in Fig. 1 are identical.

Although the method described in this study can be applied to both 532 nm channels (parallel and perpendicular polarization), only the results from the 532nm perpendicular channel are presented.

The CALIPSO surface and transient response function (thick blue curve in Fig. 2) can be accurately estimated using the surface peak and tail signal relation from CALIPSO surface returns. The red curve represents the shape of the measured surface and transient response for the case where the surface is centered on a range bin (i.e., when the surface backscatter is coincident with the sample timing). The yellow line indicates the location/timing of the surface backscatter signal. For the same land surface, the shape of measured surface return varies as a function of the timing offset between the peak of the surface backscatter and the sample timing. The green and black curves are the measured surface signal and transient response when the land surface is 7.5 meters below and above the center of the 30-meter range bin, respectively.

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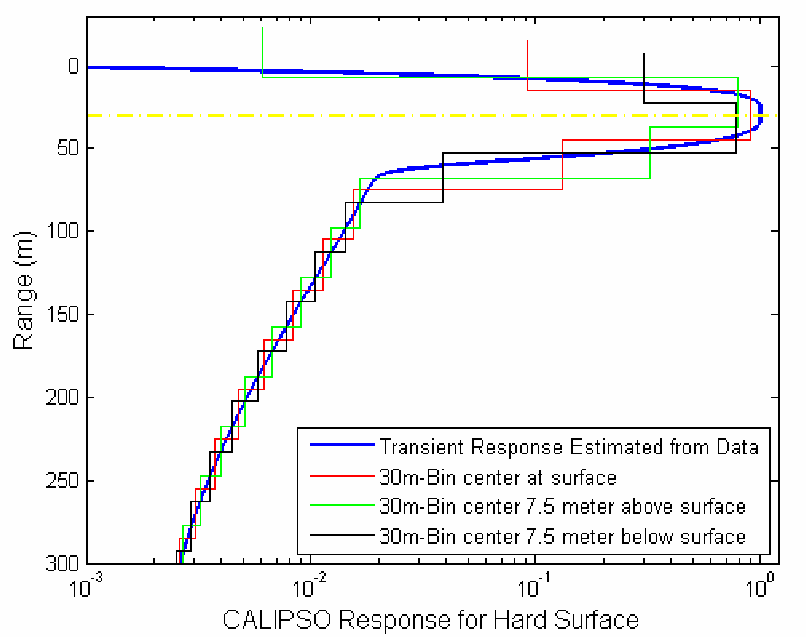

Fig. 2. CALIPSO's transient response (thick blue curve) derived from surface tail/peak ratios of all land surface data, scaled to the peak value. The red, green and black curves are CALIPSO surface returns at 30-meter vertical resolution, while the surface is at different locations within the 30-meter surface bin.

Using the CALIPSO receiver transient response function (Solid blue line of Fig. 2) derived from CALIPSO's land surface data, the distance between land surface and the center of CALIPSO's 30-meter surface range bin can be estimated using two different methods (Fig. 3),

Peak Signal Shape Method: compute backscatter difference between two range bins adjacent to the peak surface bin and divide by the peak surface bin:

$$M_1 = \frac{\left[\beta(\mathrm{p+1}) - \beta(\mathrm{p\text{-}1})\right]}{\beta(\mathrm{p})} \tag{1}$$

Tail-to-Peak Ratio Method: compute the integrated backscatter of the range bins starting from the third range bin after the observed surface peak to the 12th range bin after the observed surface peak and divide by the backscatter from the first range bin after the peak surface range bin times 2,

$$M_2 = \frac{\sum_{3}^{12} \beta(\mathrm{p+i})}{2\beta(\mathrm{p+1})} \tag{2}$$

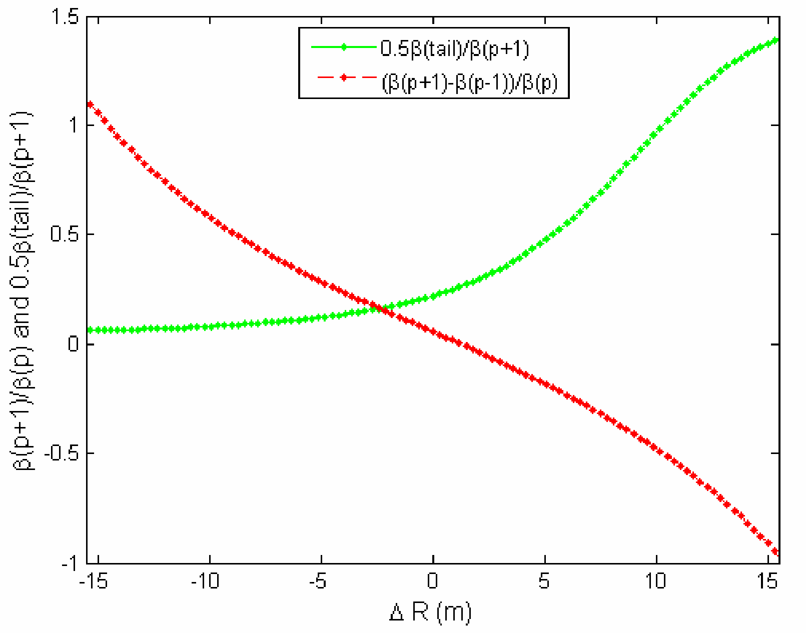

Fig. 3. Relation between tail/peak ratios (y-axis) and the distance between land surface and center of CALIPSO's 30 meter surface bin.

For most land surfaces in January 2007, these two methods provide almost identical results when the backscatter is dominated by the surface itself (Fig. 4). Exceptions are surface signal that have a low signal-to-noise ratio and saturated peak signals. For data from the summer months in areas with vegetation, the two methods exhibit some differences. For these cases, the second method is relatively less sensitive to vegetation type, The second method is also less likely to be affected by saturation of peak backscatter from snow and desert surfaces. On the other hand the first method is more accurate when moderately thick clouds are present. Most of the results shown in this paper were generated using the second method.

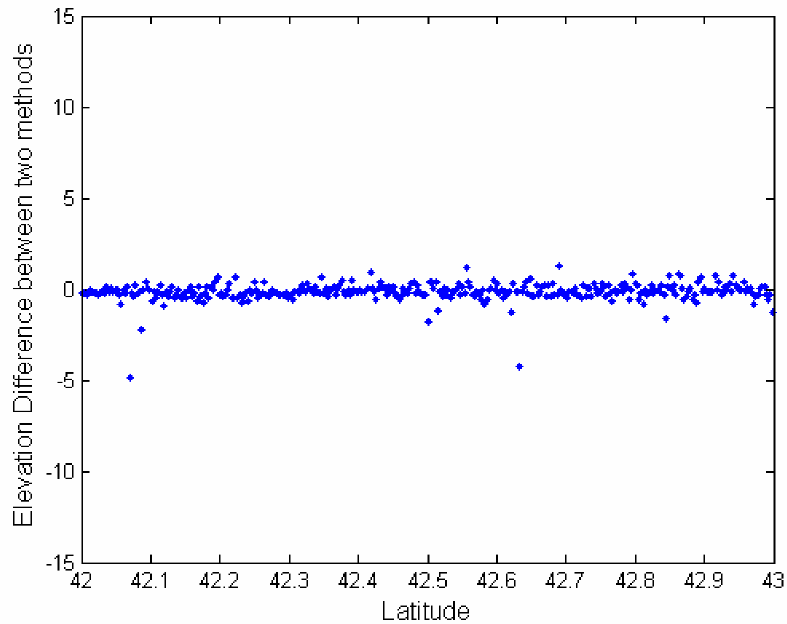

Fig. 4. Surface elevation difference (m) between the two methods as an example. The difference between the two methods is normally less than 0.5 meter when the peak signal is not saturated. The difference increases for highly reflecting snow surfaces when the peak signal saturates and affects the accuracy of the Peak Signal Shape Method.

3. Comparison with Shuttle Radar Topography Mission (SRTM) and USGS NED elevation maps

Applying the EIT technique, land surface elevation was derived for each CALIPSO lidar profile using the following procedure,

- Perpendicular channel surface bin search: Search for the first maximum 532nm perpendicular backscatter range bin, starting from lowest altitude bin.
- Three channel surface range bin comparison: Perform the same search on 532nm total (perpendicular + parallel) backscatter, and compare with 532nm perpendicular channel result. For backscatter profiles with good signal-to-noise ratios (SNR), the results should agree. When disagreement occurs, choice will be made based on further analysis of SNR and saturation.
- Apply the EIT technique for surface elevation estimation: Estimate the distance between the land surface and the center of the 30-meter 532nm perpendicular surface range bin using the EIT technique.

Figure 5 is a 1 arc second (~30-meter horizontal resolution) land surface elevation map from United States Geological Survey (USGS) National Elevation Database (NED), which provides information of the vegetation free surface altitude. The NED data source is a high resolution digital elevation map determined from photogrammetric mapping and airborne lidar elevation data and is updated every 2 months. The data are downloaded from USGS' Seamless Data Distribution System. The white line indicates the CALIPSO orbit track. The land surface elevation derived from CALIPSO using the EIT technique from this study is the red curve in Fig. 6. Figure 6 also has the CALIPSO surface altitude with its standard 30 meter vertical sampling resolution (yellow dots), the land surface or dense canopy top elevation from the 3 arc second (90-meter horizontal resolution) Shuttle Radar Topography Mission (SRTM) data (blue dot-dashed curve) collected during February 2000 [6-7], and the 1 arc second surface elevation from NED (light green).

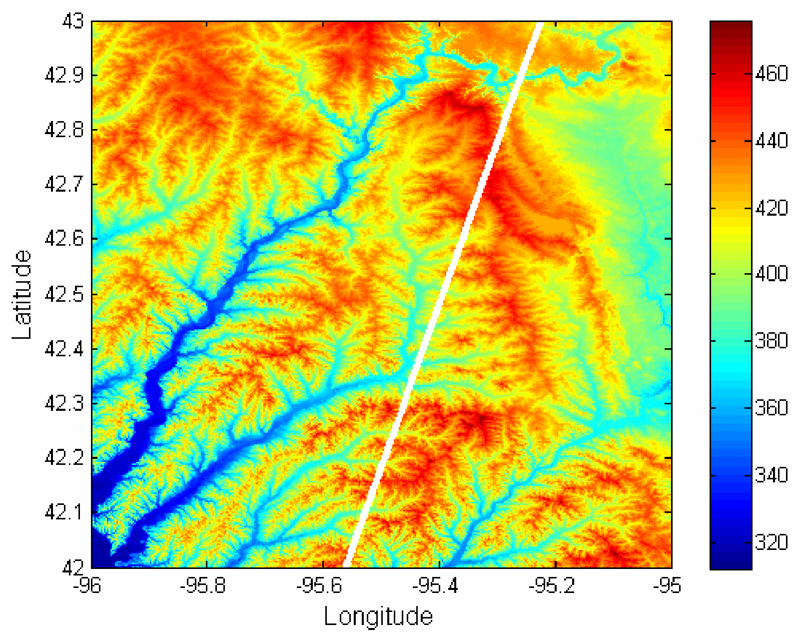

Fig. 5. The 1 Arc second USGS national elevation database (NED) land surface elevation map around the CALIPSO orbit track (while line). The unit of the elevation in the color-bar is meter.

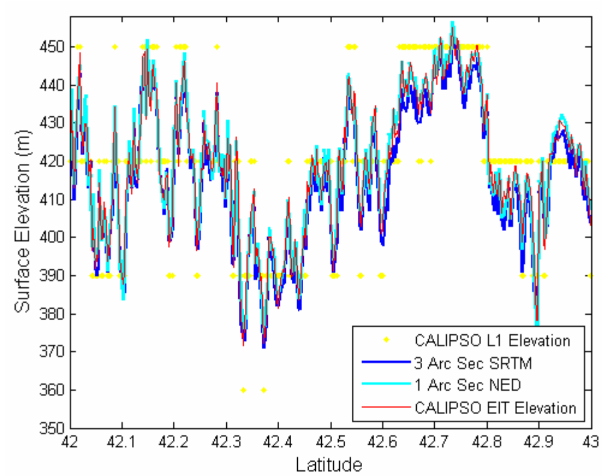

Fig. 6. The land surface elevation comparisons among the standard 30 meter CALIPSO data product (yellow dots), the 3 Arc second surface elevation from Interferometric Space Radar Topography Mission (SRTM) (blue dot-dashed line), the 1 Arc second surface elevation map from National Elevation Database (NED) (light blue line), and the single shot CALIPSO land surface elevation derived from the EIT technique (red line).

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From Fig. 6, it is apparent that the EIT technique provides a significant improvement to the surface elevation retrieval compared to the standard CALIPSO surface altitude data products. The patterns of the terrain, with all the fine details, agree well with both the SRTM and the NED surface elevation data.

Comparing with the NED 1 arc second map, the bias of the EIT method using CALIPSO data is less than 2 meters (red curve in Fig. 7, which is a 5-km moving average of the EIT and NED elevation differences). The difference between NED and EIT with single shot data has a standard deviation of about 2.5 meters, and can be reduced if the NED data are averaged to the exact CALIPSO 90 meter footprint. The bias between the CALIPSO EIT method and the SRTM map is also within 2 meters (blue curve). With an improved pointing knowledge and faster onboard clock, both the biases and the standard deviation would be reduced.

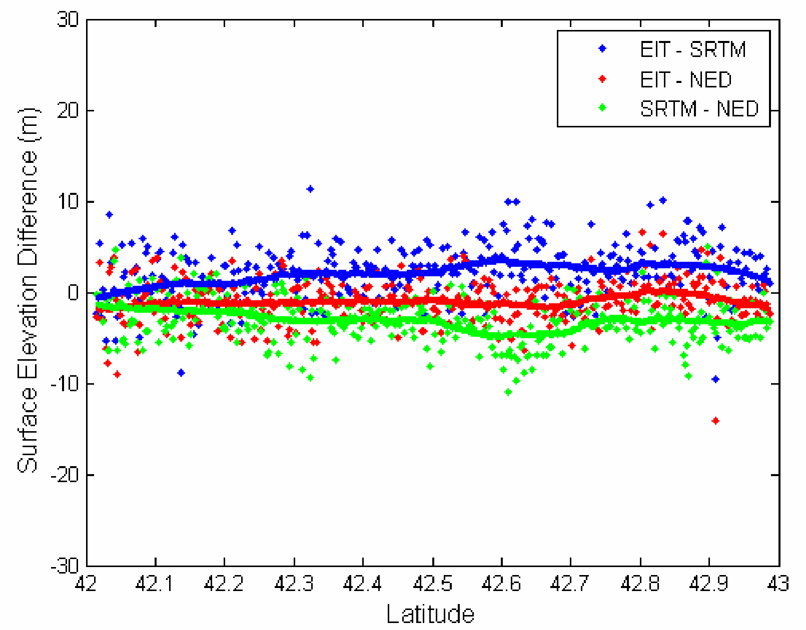

Fig. 7. Land surface elevation individual differences (dots) and differences averaged over 5 km along track (line): CALIPSO EIT technique vs 1 Arc second NED (red); 3 Arc second SRTM (blue) vs 1 Arc second NED (green).

We see similar agreement between the SRTM and the CALIPSO EIT method for other orbits, and for different geographic regions on all continents.

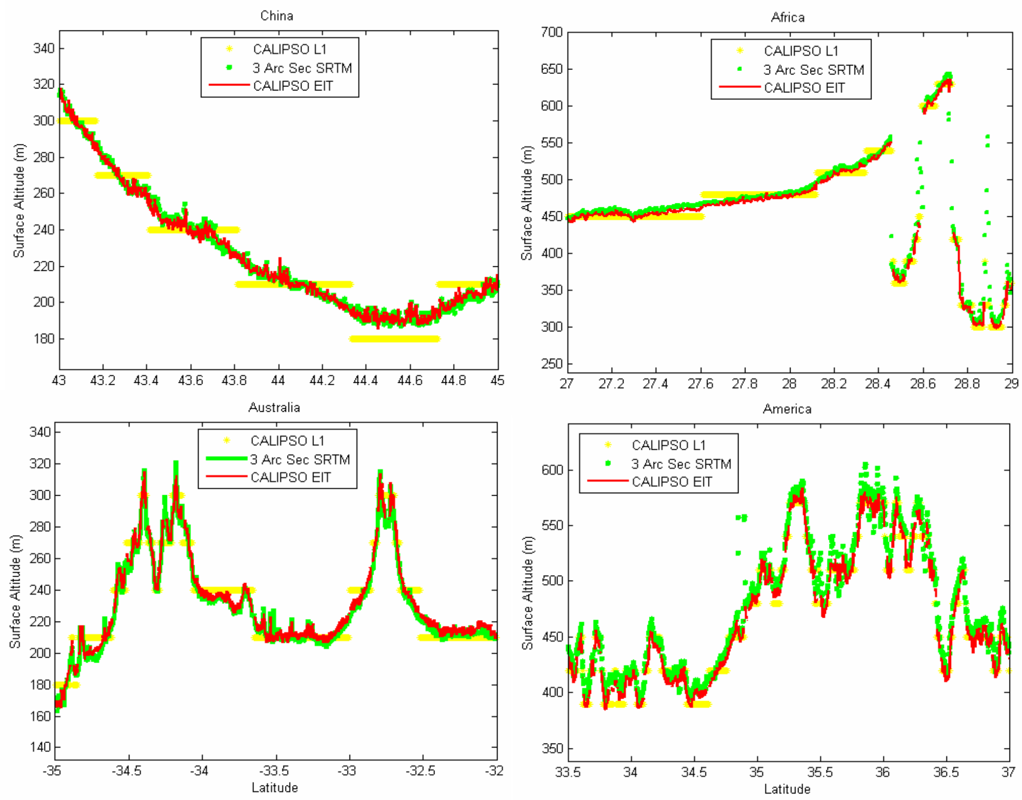

Fig. 8. Land surface elevation comparisons between EIT technique with single shot CALIPSO (red line) data and SRTM 3 Arc Second data (green dots).

Figure 8 shows more examples of comparisons between the CALIPSO EIT (red line) and the SRTM (green dots). The biases between the CALIPSO EIT method and the SRTM are around 2 meter while the standard deviations are around 3 meters. The differences between the elevations derived from the CALIPSO EIT and the SRTM are within the 10-16 meter objective of the SRTM project [3]. In most cases the biases and standard deviations of the EIT method are similar to the GLAS – SRTM comparisons [8]. There are cases, however, where we see systematic biases between the EIT and the SRTM that are likely related to the different sensitivities to vegetation canopy and surface slopes within the footprint.

4. Summary

A new technique for lidar altimetry, named the "*Elevation In Tail* (EIT)" technique, is introduced in this study. This technique can provide an order of magnitude or better improvement in land surface elevation measurement compared to the peak detection surface elevation algorithm. This technique is applied to CALIPSO data and the surface elevation retrieved using this method is in good agreement with both the National Elevation Database (NED) and the Space Radar Topography Mission (SRTM) data.

The EIT technique does not require a short transmitted laser pulse width or very fast receiver electronics and digitization. However, with a faster onboard clock and digitizers (14 bit, > 100 MHz are now available in radiation hardened packages), it should be possible to reduce the uncertainty of the surface elevation to 0.1 meter or better by decreasing the range sampling interval to 1 meter while maintaining the CALIPSO laser pulse width at 20 ns.

Allowing the laser to have longer pulse widths provides greater flexibility in designing laser efficiency and reliability – both critical to space applications. The ability, shown here, of high accuracy surface mapping combined with CALIPO's high dynamic range and polarization sensitivity, will open up new applications for space-based lidars.

There is an ongoing study which uses the elevation differences between the two methods (peak shape, and tail-to-peak ratio), and between the two polarization channels for vegetation canopy studies. We are also investigating the application of this method for bathymetry studies with CALIPSO data.

Acknowledgment

This study is sponsored by NASA the MIDAS project of Radiation Science Program under Drs. Hal Maring and Don Anderson.